Influences of Laser Spot on High-Speed Welding for Cr-Plated Sheet

Both 0.19- and 0.21-mm-thick samples were tested with a combination of focus and cylindrical lenses at different speeds

BY J. ZHAN AND M. J. YANG

ABSTRACT

Focusing on thin sheet high-speed laser welding, this study used 0.19- and 0.21-mm-thick, chromium-plated sheet as the research object and studied influences of the elongated spot length on the thin sheet laser welding speed when adopting butt joint welding by different focus elongated spot patterns from both theoretical and experimental points of view. It showed from the test result that compared with the normal spot pattern, the welding speed was increased by 41.6% for 0.19-mm-thick, chromium-plated sheet when the laser power was 1.5 kW and elongated spot length was 4.3 mm, while the welding speed was increased by 30.5% for 0.21-mm-thick, chromium-plated sheet upon elongated spot butt joint welding. Furthermore, compared with the normal spot pattern, sagging of the weld joint end face resulted by the elongated spot would be greatly reduced. Thus, it was clear that the welding speed for the thin sheet could be increased with the weld joint quality improved when the suitable elongated spot pattern was adopted.

Introduction

Chromium-plated sheet has a high melting point for the coating and requires a high welding speed. Due to high resistivity of the chromium layer, conventional resistance welding could not guarantee weld quality and speed. Compared with traditional welding methods, laser welding is a high-energy-density welding process with high welding speed, high efficiency, small deformation, and good weld quality.

Cao et al. (Ref. 1) found that the fusion zone area and width decreased with increasing welding speed, the heat-affected zone (HAZ) width was very narrow ranging from 0.2 to 0.5 mm and decreased with increasing welding speed, and the loss of ductility was mainly due to the presence of micropores and aluminum oxides.

Capello and Hong et al. (Refs. 2, 3) found that preheat treatment before welding and postheat treatment after welding showed a reduction of microfissures and improved tensile and fatigue properties.

P'ng et al. (Ref. 4) studied Q-switch Nd:YAG laser welding of 60 μm thin foils of AISI 304 stainless steel and found that improved aesthetics, reduced porosity, improved energy efficiency, and absence of hot cracking/thermal distortion were the chief benefits observed in laser welding over resistance seam welding.

Sharma et al. (Ref. 5) evaluated the size and shape variability of weld zones for laser welded, advanced high-strength steels with various combinations of types, coatings, and thicknesses, as well as researched laser welding for different thickness sheets and studied weld shape by altering laser parameters.

Tan et al. (Ref. 6) studied the effect of laser parameters on the weld quality and considered that surface roughness Ra had an influence on the fraction of energy absorbed, therefore affecting penetration depth, and also found the higher power density produced a stronger weld joint.

Y. Zhao (Ref. 7) found that in a root opening free, lap joint configuration of 0.4-mm-thick, galvanized SAE1004 steel sheets, severe spatter and porosity were produced in the welds, and a prescribed root opening was needed to vent the pressurized zinc vapor and then obtain an acceptable joint. Experiments validated that the desired high-quality welds can be achieved using the optimal parameters.

F. Kong (Ref. 8) found that the keyhole dynamic behavior as well as liquid flow in the molten pool depended directly on the behavior of zinc vapor at the faying surface, an increase in welding speed could cause a slight reduction in the plasma spectrum intensity and would decrease the depth of weld penetration, plus the depth of weld penetration would increase if the zinc coating was removed.

J. P. Coelho (Ref. 9) studied the influence of the dimensions of the laser beam spot on weld strength and found that the weld tensile strength could be increased by defocusing the beam. Getting a "line spot" by using a cylindrical lens could overcome that the maximum laser power available had a limit, while as the area of the laser spot on the sample increased, more power was necessary to achieve the critical specific energy required for a good weld.

Y. Shi (Ref. 10) studied the lap welding of JSC270CC steel and A6111-T4 aluminum alloys by a dual-beam YAG laser with the continuous wave (CW) and pulse wave (PW) modes, and found that the dual-beam laser welding could effectively reduce or avoid the formation of blowholes in the welded joints.

As the requirement for welding speed improved and laser power increased, some weld defects, such as melt through and concavity, would be experienced when laser welding thin sheet, approximately 0.2 mm thick. It would have important, promising applications to carry out research on high-speed laser welding for thin sheet. However, at the present time, research in

KEYWORDS

Laser Welding
Chromium-Plated Sheet
Elongated Spot
Welding Speed

J. ZHAN (zhanjian@imech.ac.cn) *and M. J. YANG are with the Institute of Mechanics, Chinese Academy of Sciences, Beijing, China.*

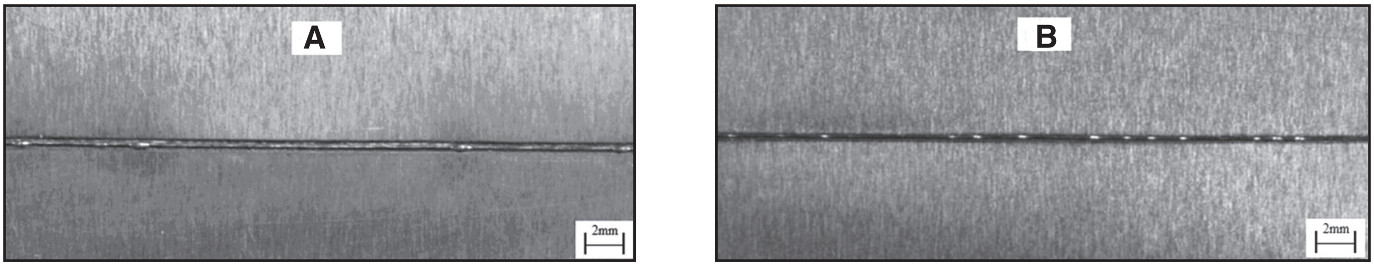

Fig. 1 — Laser welding surface appearance. A — Front side; B — the back. Laser power density is 6.97 × 10^5 W/cm^2, welding speed is 45 m/min.

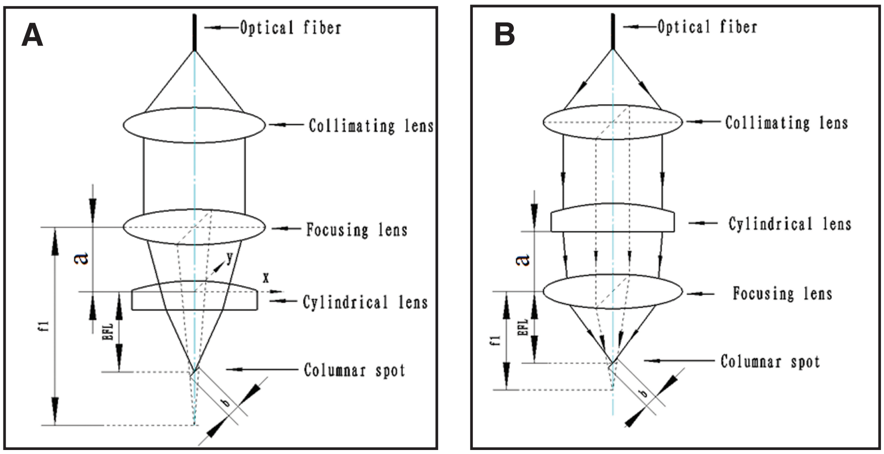

Fig. 2 — Schematic diagram of columnar laser spot welding. A — Cylindrical lens behind focusing mirror; B — cylindrical mirror in front of focusing mirror.

such field is insufficient.

Based on the characteristics of welding for thin sheet, this research analyzed and studied how the quality of the weld joint-would be influenced by the laser space distribution during high-power laser welding. It did this through adjustment and control of the laser parameters in the course of a welding test where the elongated spot pattern was realized, through a combination of cylindrical and focusing lenses.

Working Principle of Elongated Spot

Since 0.19- and 0.21-mm-thick sheets were adopted as the test subjects, some defects, such as humping, might occur in the weld where the density of the laser power was too high (refer to Fig. 1). With regard to 0.20-mm-thick sheet, the laser welding was mainly realized through the adjustment of input power density and action time of the laser.

Assume that laser action time was $t_1 = 2r/v$, wherein r was the laser spot radius and v was the welding speed, and the thermal conductivity depth of laser was $h_1 = \sqrt{\partial \cdot t_1}$ wherein ∂ was the thermal diffusivity coefficient with the laser focusing spot to be 2r × b elongated spot, the power density would be $F_2 = P/(\pi \cdot r^2 + 2r \cdot (b - 2r))$.

The laser action time was $t_2 = b/v$ and thermal conductivity depth $h_2 = \sqrt{\partial \cdot t_2}$, wherein b was the length of the major axis of the columnar spot. Assume the major axis $b = 4r$, and the ratio of the laser power density was $F_2/F_1 = \pi/(4 + \pi) = 0.44$, the laser action time ratio $t_2/t_1 = 2$, and the heat conduction depth ratio $h_2/h_1 = 1.414$. The purpose for focusing the laser beams into an elongated spot was to increase the laser action time and laser penetration rate under the premise of maintaining the material melting and welding speeds. Here, the columnar spot b needed to meet two conditions. One was that the material should be melted under the laser action when the value of b had an upper limit, i.e., reached the maximum value. The other was that the material did not strongly vaporize under the action of the laser when b had a lower limit, i.e., a minimum value.

Table 1 — Laser Parameters

Laser Power (kW)	Fiber Diameter (mm)	Focal Length of Collimating Lens (mm)	Focal Length of Focusing Lens (mm)
1.5	0.6	86	100

The Formation Mechanism of Columnar Spot

Based on the characteristics of cylindrical lens focuses only in one direction, a cylindrical lens and focusing mirror were used in combination to change the focal length of the two lenses as well as their relative positions to generate focused columnar spots of different sizes. The schematic diagram is shown in Fig. 2.

D_0 was the diameter of the incident light beam after passing the collimator lens, f_1 the focal length of the focusing lens, f_2 the focal length of the cylindrical lens, and a the spacing of the two lenses. If the focusing lens was in front of the cylindrical lens, as shown in Fig. 2A, then in the x direction, the combined focal length of the two lenses could be obtained from equation 1:

$$f' = f_1 \cdot f_2 / (f_1 + f_2 - a) \qquad (1)$$

The distance from the focus to the cylindrical lens was given by 2:

$$EFL = f' (1 - a/f_1) \qquad (2)$$

Put 1 into 2, and we get:

$$EFL = (f_1 - a) \cdot f_2 / (f_1 + f_2 - a) \qquad (3)$$

In the y direction, the cylindrical lens did not have focusing effect, and the spot size b could be obtained according to the triangle similar relationship by 4:

$$b = (f_1 - a)^2 D_0 / [(f_1 + f_2 - a) \cdot f_1] \qquad (4)$$

As shown in Fig. 2B, when the focusing mirror was behind the cylindrical lens, EFL, the distance from the focal point to the focusing mirror, and the elongated spot length b could be obtained from 5 and 6, respectively:

$$EFL = (f_2 - a) \cdot f_1 / (f_1 + f_2 - a) \qquad (5)$$

$$b = f_1 \cdot D_0 / (f_1 + f_2 - a) \qquad (6)$$

The value of the minor axis of the elon-

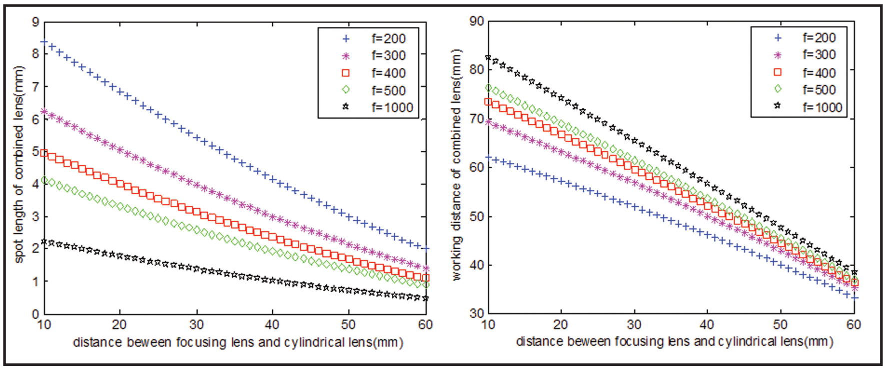

Fig. 3 — Laser focused on the workpiece through focusing lens/cylindrical lens.

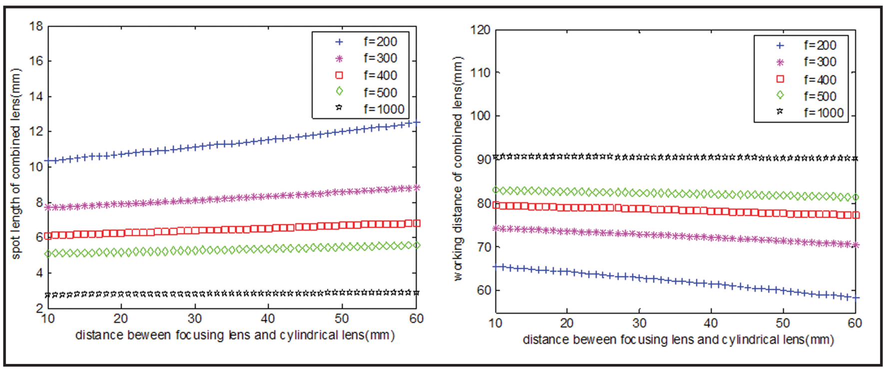

Fig. 4 — Laser focused through cylindrical lens/focusing lens onto the workpiece.

gated focus spot was calculated by the following equation:

$$d = d_0 \cdot f' / f_3 \quad (7)$$

Where d_0 was the diameter of the fiber, f_3 was the focal length of the collimating lens, and if the laser spot was a circular focus spot, f' was the focal length of the focus lens. In this test, the following values were given: $d_0 = 0.6, f_1 = 100$ mm, $f_2 = 200$ mm, $f_3 = 86$ mm, and $a = 40$ mm, so the diameter of the elongated focus spot was 0.54 mm, if only using $f_1 = 100$ mm without the cylindrical lens, the diameter of the circular focus spot was 0.70 mm.

Adjustment of b, the value of the columnar spot length, could be realized by changing the value of f_1, f_2, and a. Figure 3 shows the size of a focused spot formed on the workpiece after going through the focusing lens/cylindrical lens with the curve reflecting the change of working distance with the spacing between lenses in the combination and focal length of the cylindrical lens. Figure 4 shows the size of a focused spot formed on the workpiece after going through the cylindrical lens/focusing lens with the curve reflecting the change of working distance with the spacing between lenses in the combination and focal length of the cylindrical lens, wherein, $D_0 = 30$ mm.

When the focal length of the cylindrical lens was increased, the focused spot length of combination lens was decreased, while the working distance of the laser butt joint welding was increased. As shown in Fig. 3, when the laser beams first went through the focusing lens and then the cylindrical lens, the lengths of the focusing spot and welding working distance were reduced as the spacing of the two lenses increased. As shown in Fig. 4, when the laser beams first passed through a cylindrical lens and then the focusing lens, the length of the focusing spot was increased as the spacing of the two lenses increased, while the welding working distance was reduced. Compared to Fig. 3, the change was not significant. In this experiment, a combination consisting of a cylindrical lens with focal length 200 mm and focusing lens with focal length 100 mm, plus the 0.19- and 0.21-mm-thick, chrome-plated sheets, were used to study the improvement of laser energy distribution with columnar spot and speed increase of the laser butt joint welding by prolonging the time of laser action.

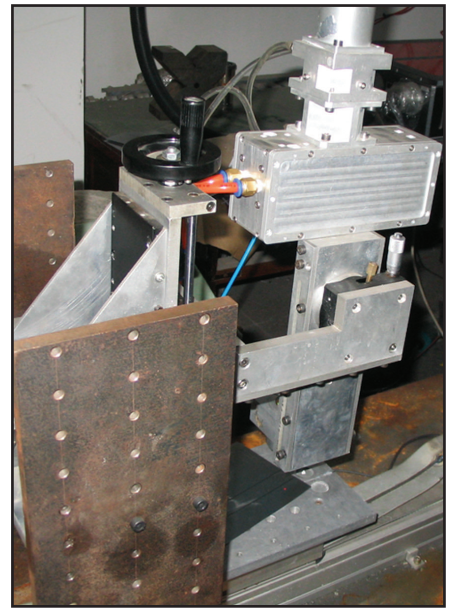

Fig. 5 — Laser welding equipment used in the study.

Laser Welding Experiments

Laser Welding Equipment

Figure 5 shows the laser welding equipment. For the laser, a continuous YAG semiconductor laser was used with a maximum power of 2 kW, wavelength of 1064 nm, in addition to a focus lens with a focal length of 100 mm.

Laser Welding Experiments

A 1.5-kW laser was used for butt joint welding a 0.19-mm, Cr-plated sheet of a certain base material. The combined cylindrical lens with a focal length of 200 mm and a focusing lens with focal length of 100 mm adjusted the spatial distribution of the focusing spot to implement laser welding with a spot of a different length b — Fig. 2. The parameters of the laser are shown in Table 1 and that of the focusing mirror set in Table 2. The first parameter applied to a focusing laser beam through cylindrical lens/focusing lens on the workpiece, and the second parameter applied to focusing a laser beam through the focusing lens/cylindrical lens on the workpiece.

Three different focusing crafts were used. First was a focusing lens with a focal length of 100 mm to directly focus the laser beam on the workpiece surface. The

Table 2 — Parameters of the Combination of Lens

No.	a (mm)	f' (mm)	EFL (mm)	b (mm)
1	20	71	64	10.7
2	40	77	46	4.3

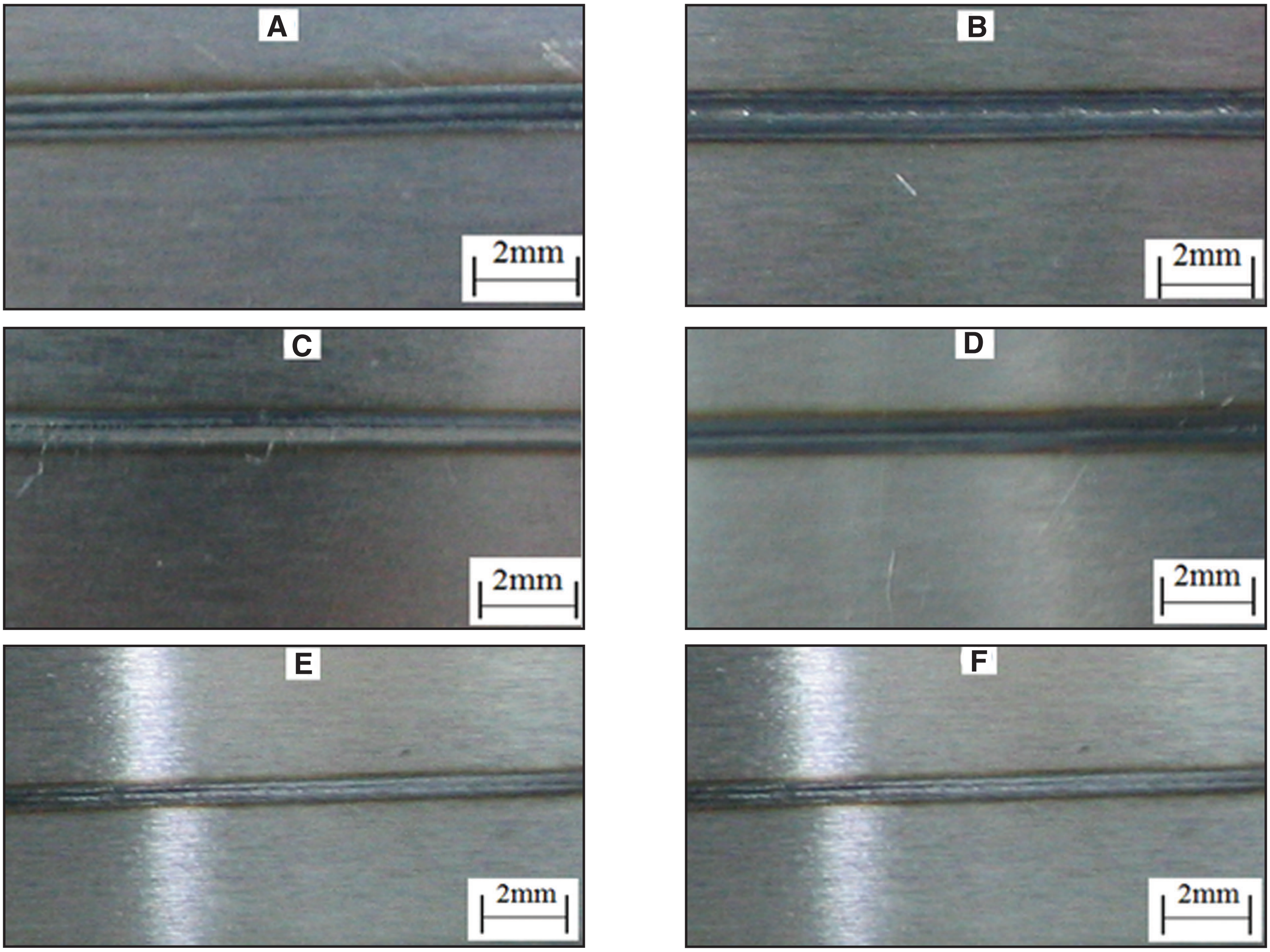

Fig. 6 — Surface appearance of weld from laser butt joint welding.

maximum speed of butt joint welding was 18.5 m/min and a weld width of 1 mm. The appearance of the weld surface is shown in Fig. 6A and B, wherein A is the front side of the weld and B the back. Second was a cylindrical lens/focus lens to aim the laser beam onto the workpiece. The parameters of the combination lens is shown in No. 1, Table 2. The maximum speed of butt joint welding was 23.1 m/min, weld width 0.85 mm, and the width of HAZ 0.25 mm. The weld surface appearance is shown in Fig. 6C and D, wherein *C* was the front side and *D* the back. Third was the focusing lens/cylindrical lens to aim the laser beam on the workpiece. The parameters for the combination lens is shown in No. 2, Table 2. The maximum butt joint welding speed was 26.2 m/min with weld width 0.65 mm. The weld surface appearance is shown in Fig. 6E and F, where *E* was the front side and *F* the back.

With respect to no application of cylindrical lens, the welding speed could be increased by 41.6% when the columnar spot length was 5.4 mm, while the columnar spot length was 10.7 mm, the welding speed could be increased by 24.8%. Therefore, compared to the ordinary laser spot welding, the columnar spot could have a higher welding speed.

Table 3 — Parameters and Experimental Results for Combination of Lens

No.	f_2 (mm)	a (mm)	b (mm)	Welding Speed (m/min)	Remarks
1	1000	30	2.2	19.3	Focusing mirror close to the welding workpiece
2	500	30	2.6	20.8	Cylindrical lens close to the welding workpiece
3	200	40	4.3	26.2	Cylindrical lens close to the welding workpiece
4	200	30	5.4	24.6	Cylindrical lens close to the welding workpiece
5	200	20	10.7	23.1	Focusing mirror close to the welding workpiece

Results and Analysis

Influence of Columnar Spot on Welding Speed when Cylindrical Lens with Various Focal Lengths is Combined with a Focusing Mirror

Welding a chrome-plated sheet was carried out the same as in the laser welding experiments section using a laser with a power of 1.5 kW. Laser parameters are shown in Table 1. The focal length of the focusing lens with f_1 = 100 mm, plus cylindrical lens with focal lengths of 200, 500, and 1000 mm, were combined with a 100-mm focusing lens, respectively, and the parameters as well as welding test results are shown in Table 3.

Just like in that section's experiment, when only 100-mm focusing lens was used, the 1.5-kW laser welding speed was 18.5 m/min, indicating that the welding speed could be increased through a cylindrical lens. Maximum welding speed was obtained with a columnar spot of 4.3 mm.

Laser Welding Experiment on the 0.21-mm Sheet

Butt joint welding experiments were made using a 200-mm cylindrical lens and a 100-mm focusing lens, respectively, welding base material 0.21 mm in thickness, and laser power of 1.5 kW. The relationship between welding speed and parameters of the lens combination were obtained, as shown in Table 4.

When a cylindrical lens was not used, after focusing at a focal length of 100 mm, the maximal speed of laser welding was 16.9–18.5 m/min, averaged at 17.7 m/min. When a cylindrical lens with a focal length of 200 mm was used, if parameter 1 in Table 4 was used, the columnar spot was 4.3 mm, and the maximum welding speed was 23.1 m/min. Compared to a circular spot, which was not used, the welding speed was increased by 30.5%. If parameter 2 was used, the maximum welding speed was 20.0 m/min. Compared to the circular spot, the welding speed was increased by 13.0%.

In the working principle of elongated spot and formation mechanism of columnar spot sections, the effect of cylindrical lens increasing butt joint welding speed (41.6%) for 0.19-mm sheet through a test was made. It was found that without increasing laser power, the thinner the welded base material, the more obvious the effect of the columnar spot.

In Fig. 7, laser parameters for No. 1–4 were as follows:

1. Focusing mirror with focal length of 100 mm, workpiece thickness of 0.21 mm
2. Focusing mirror with focal length of 100 mm was put close to the workpiece and combined with a cylindrical lens with focal length of 200 mm, workpiece with thickness of 0.21 mm
3. Focusing mirror with focal length of 100 mm, workpiece thickness of 0.19 mm
4. Focusing mirror with focal length of 100 mm was put close to the workpiece and combined with a cylindrical lens with focal length of 200 mm, workpiece with thickness of 0.19 mm.

After etching the weld structure, it was observed after laser welding that the depression value of parameters 1 and 3 in Fig. 7 was about 10% of the sheet thickness (in Fig. 7, thickness of specimens 1 and 2 was 0.21 mm; that of 3 and 4 was 0.19 mm). With columnar spot mode, the degree of protuberance or recesses on the weld (see 2 and 4 in Fig. 7) was significantly smaller than that on the weld without using a cylindrical lens (see 1 and 3 in Fig. 7). This was because with columnar spot mode, the beam energy became uniform and the formation of weld pool during the welding process became stable without material strongly vaporizing or impact, improving the weld quality. It could be seen that columnar spot reduced the projections and recesses of the welds, reducing weld defects, as also reported by A. Haboudou (Ref. 11), who found that dual spot welding would significantly reduce the porosity rate because dual spot welding had a stabilizing effect on the weld pool.

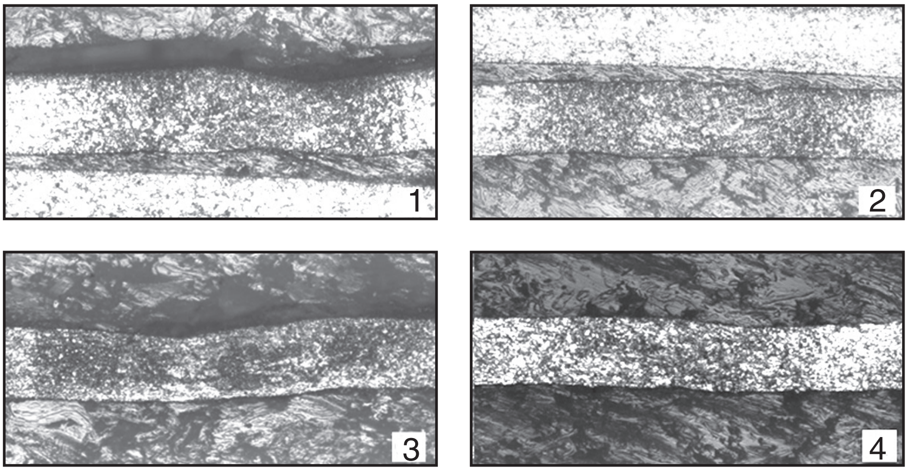

Fig. 7 — A cross-sectional view of the weld.

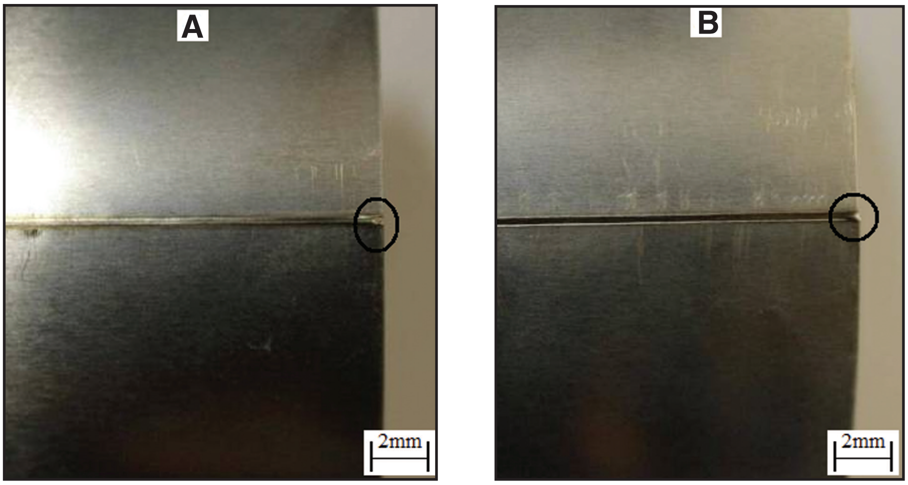

Fig. 8 — The end face depression contrast. A — Ordinary spot; B — columnar spot.

Weld End-Face Experiment

When comparing the end surface depression by ordinary light and columnar light spots, it was found that the depression by ordinary spot laser welding measures 0.8 mm in length, as shown in Fig. 8A, while the depression left by columnar spot laser welding was almost invisible. Use of a columnar spot in laser welding could reduce or eliminate the depression on the end face of the weld and improve weld quality.

Tensile Test and Cupping Test

A tensile test was carried out on the welded 0.19- and 0.21-mm-thick, chrome-

Table 4 — Columnar Spot Contrast Test on 0.21-mm-Thick Chrome Plate

No.	f_2 (mm)	a (mm)	Welding Speed (m/min)	Remarks
1	200	40	23.1	Cylindrical lens close to the welding workpiece
2	200	30	20.0	Focusing mirror close to the welding workpiece

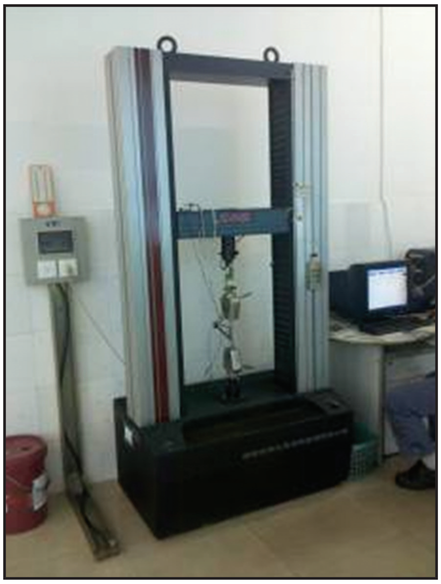

Fig. 9 — Tensile test rig.

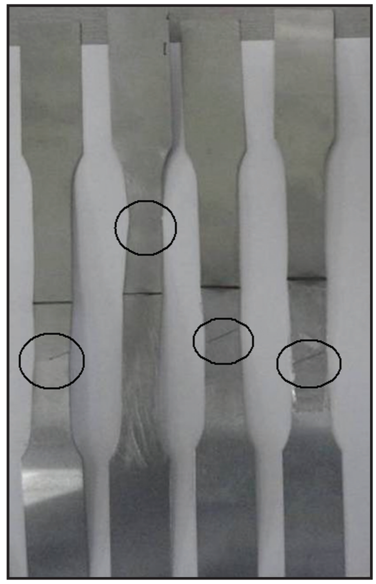

Fig. 10 — Tensile test results in blocks.

Table 5 — Cupping Test Results

No.	Welding Speed (m/min)	Weld Cupping Value (mm)	Thickness (mm)
1	17.7	5.39	0.21
2	23.1	5.59	0.21
3	18.5	5.11	0.19
4	21.6	5.76	0.19

plated sheets under different laser parameters for laser butt joint welding to test the yield strength of the weld joints. The tensile test rig (5 kN) is shown in Fig. 9 and the tensile specimens in Fig. 10. All the fractures were plastic fractures at locations other than the welds.

The tensile test in Fig. 10 indicated the tensile strength of the weld exceeded that of the base material. An Erichsen cup test was used for reflecting the plastic properties of the weld. Table 5 shows the cupping test results of various laser parameters with weld test blocks of which No. 1–4 was defined in Fig. 7 of the laser welding experiment on the 0.21-mm sheet section. From the cupping test results, it could be seen that the cupping values of welds were greater after using columnar spot. Compared with laser welds using an ordinary spot, in the cases of 0.19 and 0.21 mm, the cupping values of laser welds resultant from using a columnar spot were found to have increased by 12.7 and 3.7%, respectively. The cupping value was the pressed depth value of a spherical punch when the first crack appeared on the specimen by pressing the test specimen with the weld, which reflected the plastic properties of the material. After going through a cylindrical lens, the beam pattern of the columnar spot was improved, and the laser energy concentrated at the center of the weld was reduced, thus reducing weld defects and enhancing weld quality.

Conclusion

In previous work, the relationship between laser spot mode and welding speed in high-speed welding was investigated. By metallographic analysis of the shape of the molten weld pool, tensile test, and cupping test, the influence of laser parameters on weld quality was studied. The following conclusions were reached:

1. For 0.19-mm-thick, chrome-plated sheet, the laser beam was passed through the focus lens/cylindrical lens (speed 26.2 m/min) and cylindrical lens/focus lens (speed 23.1 m/min). Compared to not using a cylindrical lens (speed 18.5 m/min), the welding speed was increased by 41.6 and 24.8%, respectively.

2. In the case of 0.19-mm-thick, chrome-plated sheet, maximum welding speed (26.2 m/min) was obtained when the columnar spot was 4.3 mm, at laser input of 1.5 kW.

3. For butt joint welding experiments on 0.21-mm-thick, chrome-plated sheet, with the laser power at 1.5 kW, the maximum welding speed was 17.7 m/min when the cylindrical lens was not used and 23.1 m/min when a combination of cylindrical lenses were used, reflecting an increase of 30.5%.

4. When the laser input power remained the same, the thinner the welding base material, the greater the contribution of columnar spot to welding speed.

5. Through cross-section corrosion of the weld, it was found that after improving the beam mode of the columnar spot, raised or sunken welds were significantly reduced. Compare the result with weld ports depression, and we found that welding with cylindrical lens basically eliminates end face depression and improves weld quality.

6. Through a weld tensile test, none of the breaks found occurred in the weld area, indicating that the weld strength was higher than the base material. Compared to the result with a cupping test, it was found that use of the cylindrical lens improved the cupping value, i.e., the quality of welds.

References

1. Cao, X., and Jahazi, M. 2009. Effect of welding speed on butt joint quality of Ti–6Al–4V alloy welded using a high-power Nd:YAG laser. *Optics and Lasers Engineering* 47: 1231–1241.

2. Capello, E., Chiarello, P., Previtali, B., et al. 2003. Laser welding and surface treatment of a 22Cr-5Ni-3MO duplex stainless steel. *Materials Science and Engineering A* 351: 334–343.

3. Hong, J. K., Pak, J. H., Park, N. K., et al. 2008. Microstructures and mechanical properties of Inconel 718 weld by CO_2 laser welding. *Journal of Materials Processing Technology* 201: 515–520.

4. P'ng, D., and Molian, P. 2008. Q-switch Nd:YAG laser welding of AISI 304 stainless steel foils. *Materials Science and Engineering A* 486: 680–685.

5. Sharma, R., Molian, P., and Peters, F. 2010. Geometric variability and surface finish of weld zones in Yb:YAG laser welded advanced high strength steels. *Journal of Manufacturing Processes* 12: 73–84.

6. Tan, C. W., Chan, Y. C., Leung, B. N. W., et al. 2005. Characterization of Kovar-to-Kovar laser weld and its mechanical strength. *Optics and Lasers Engineering* 43: 151–162.

7. Zhao, Y., Zhang, Y., Hu, W., and Lai, X. 2012. Optimization of laser welding thin-gage galvanized steel via response surface methodology. *Optics and Lasers in Engineering* 50(9): 1267–1273.

8. Kong, F., Ma, J., Carlson, B., and Kovacevic, R. 2012. Real-time monitoring of laser welding of galvanized high strength steel in lap joint configuration. *Optics & Laser Technology* 44(7): 2186–2196.

9. Coelho, J. P., Abreu, M. A., and Pires, M. C. 2000. High-speed laser welding of plastic films. *Optics and Lasers in Engineering* 34(4–6): 385–395.

10. Shi, Y., Zhang, H., Takehiro, W., and Tang, J. 2010. CW/PW dual-beam YAG laser welding of steel/aluminum alloy sheets. *Optics and Lasers in Engineering* 48(7–8): 732–736.

11. Haboudou, A., Peyre, P., Vannes, A. B., and Peix, G. 2003. Reduction of porosity content generated during Nd:YAG laser welding of A356 and AA5083 aluminium alloys. *Materials Science and Engineering: A* 363(1–2): 40–52.